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Juul, Nina; Münster, Marie; Ravn, Hans; Ljunggren Söderman, M.

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CHALLENGES WHEN PERFORMING ECONOMIC OPTIMIZATION OF WASTE TREATMENT

N. Juul¹, M Münster², H. Ravn³ and M Ljunggren Söderman^{4,5}

1 Risø DTU National Laboratory of Sustainable Energy, Technical University of Denmark, Denmark, Researcher, njua@risoe.dtu.dk

2 Risø DTU National Laboratory of Sustainable Energy, Technical University of Denmark, Denmark, Researcher, maem@risoe.dtu.dk

3 RAM-lose, Denmark, DrTechn, hans.ravn@aeblevangen.dk

4 Energy and Environment, Chalmers University of Technology, Gothenburg, Sweden, Assistant professor, maria.ljunggren@chalmers.se

5 IVL Swedish Environmental Research Institute, Gothenburg, Sweden, Researcher

ABSTRACT

New investments in waste treatment facilities are needed due to a number of factors including continuously increasing waste amounts, political demands for efficient utilization of the waste resources in terms of recycling or energy production, and decommissioning of existing waste treatment facilities due to age and stricter environmental regulation. Optimization models can assist in ensuring that these investment strategies will be economically feasible.

Various economic optimization models for waste treatment have been developed which focus on different parameters. Models focusing on transport are one example but models focusing on energy production have also been developed as well as models which take into account the plants economies of scale, environmental impact, material recovery and social costs. Finally, models combining different criteria for selection of waste treatment methods in multi criteria analysis have been developed.

A thorough updated review of the existing models is presented and the main challenges and the crucial parameters to take into account when assessing the economic performance of waste treatment alternatives are identified. The review article will assist both policy makers and model developers involved in assessing economic performance of waste treatment alternatives.

Keywords: Optimization; economy; treatment; strategy

INTRODUCTION

The increasing focus on sustainability and waste management calls for decision support tools to support the waste management decisions. Many different systems analysis tools have been developed. These systems analysis tools can be grouped into two categories; 1) System assessment tools, containing e.g. life-cycle assessment (LCA) and material-flow analyses, and 2) systems engineering models, containing e.g. economic optimization and cost-benefit analyses. In this paper, a review of optimization models from the latter category – the different systems engineering models developed - is given.

Broader reviews of waste management models include Pires et. al [1] who have provided a review of systems analysis techniques, distinguishing between the above two categories. Based on a review of the EU-15 group of countries they conclude i.a. that the Southern European countries require development measures to implement more integrative solid waste management systems (applying e.g. optimization models) while other countries need more models and tools in order to rationalize their technological choices and management strategies. Furthermore, Morrissey and Browne [2] provides a review of waste management models, using three main categories viz., cost

benefit analysis, life cycle analysis and multi-criteria analysis. Finally, Seadon [2] gives a review of the complexity of waste management systems. Waste unit subsystems are here shown to be many, as are the links between different waste fractions and both internal and external systems, e.g. ministries and environment. For handling the uncertainty in waste management, Srivastava and Nema (2011) [3] has given a review of types of models and relevant papers accordingly and Finnveden et. al (2006) has illustrated the possibilities and limitations of waste management models [4].

As mentioned, waste management models can be categorised in either system assessment tools or system engineering models. Broadly speaking, system assessment tools assess solutions for the waste management system and consist of e.g. life-cycle assessment – LCA - ORWARE [5], EASEWASTE [6-8], SIWMS [9]. Tabata et. al. treat combination of LCA and multi-objective optimization on a case of eight municipalities in Japan [10]. The system is represented with transportation, and treatment processes include incineration for electricity generation, bio-methanation, material recovery, composting, bulky-waste disposal sanitary landfill, over a 25 years' study horizon. The three objectives are minimization of GHG emission, of final disposal and of treatment costs, respectively.

System engineering models on the other hand create (engineer) future solutions. For waste management it can be beneficial to both create and assess possible future solutions and, thus, work with both types of models. However, some system engineering models do assess as well as create possible future solutions.

This paper provides a thorough review focusing on waste optimisation models in terms of types of optimisation and objectives. The paper is structured as follows. First, a section describing the different types of used waste management models, focusing mainly on the systems engineering models. The next section describes the optimization models used and the main focus in the literature. The last section contains a conclusion.

TYPES OF SYSTEMS ENGINEERING MODELS FOR WASTE MANAGEMENT

Focus in this paper is a review of models for engineering future waste management systems. In general the challenge is to achieve a balance between, on one hand, the amount of parameters to take into account and the levels of detail needed, and on the other hand, the demand for reliable input data and computing time. The system engineering models are divided into five types of models:

Cost-benefit models: In cost benefit analyses, total costs are compared to total benefits, in order to identify solutions with the highest benefit to cost ratio. In choosing between different alternatives, the one with the largest positive difference between benefits and costs is chosen. Cost-benefit analyses can also be used for assessing the value of a proposed future solution. Cost benefit analyses often integrate economic and monetized costs and benefits of none marketed goods. In waste management situations, monetized cost and benefits typically include environmental effects and householder's time spent on source separation (e.g. Bruvold 1998 [11]). Cost-benefit analyses have also been used for e.g. municipal waste management in Taiwan [12].

Multi criteria decision models (MCDM): In MCDM multiple criteria are considered when making a decision. For waste management decisions, these criteria could include costs, demands, waste levels, environmental factors etc. MCDM has for example been integrated with LCA and geographical information systems (GIS) in Shmelev et al. 2006 [13]. In the article, very detailed data and a large model is discussed (145 waste generation points, 86 waste treatment centres implying approx. 90.000 integer variables, 13 mio. real variables), although only a reduced model was solved.

Simulation models: In simulation models, the future waste system is simulated in order to analyze performance, costs etc. In Sahlin et. al 2004 [14], a simulation tool using annual merit order duration curve is used (HEATSPOT). And in Lundin et. al. 2004 [15], a simulation tool using dispatch order from variable heat costs is used (MARTES).

Forecasting models: Through forecasting models the outcome of future solutions are estimated. Often forecasting is done using statistical methods like time-series analysis or econometrics. Forecasting of waste flows in the EU-countries using econometrics has e.g. been done by Skovgaard et. al. [16]. In the article waste streams in the "old" and "new" member states are compared.

Optimization models: In optimization models a function is either minimized or maximized. In many waste management models, total system costs are minimized, according to various restrictions on e.g. capacity or demand. Many types of optimization models are used for waste management, including linear programming models, interval programming, and fuzzy systems. Some optimisation models are deterministic, whereas others are stochastic, see further in the next section. Many optimisation models have been found in the literature, and the remainder of the paper will be focusing on these.

Optimisation models for waste management

Many types of optimisation models exist, most of them relevant for use in waste management. An overview of types of models developed for waste management is given in Table 1.

Optimisation models for waste management Many types of optimisation models exist, most of them relevant for use in waste management. An overview of types of models developed for waste management is given in Table 1.

Optimization is relevant when one decision-maker controls the important parts of the system in focus, e.g. optimization of an organization's operations. When several actors are involved, (e.g. controls different parts of the system) the concept of minimizing total costs is relevant under the assumption that all decision-makers aim at maximising their benefits, as this case may represent a competitive economy. Then the total costs could be regarded as the costs for society and the authority could be responsible for acting with society's best in mind (implementing policies etc). Waste management has mainly been analysed either with focus on waste recycling/depositing or waste-to-energy (WtE) solutions. Few models have integrated the two types of solutions and if they are integrated then focus is by far on one type of solution and only a rudimentary representation of the other type is modelled [17]. The EU commission have established that LCA's can be used as arguments to deviate from the Waste Hierarchy [18]. For some waste fractions different LCA's come up with deviating conclusions with regard to whether it is best to recycle the fraction or use it for energy from an environmental perspective [19;20]. As waste is a limited resource, situations will occur where there will be competition between recycling a waste fraction and utilising it for energy production. The costs of the different waste management solutions and the impact on e.g. the remaining energy system are relevant parameters to take into account, when making a choice of how to treat the relevant waste fractions.

Linear programming (LP) is widely used when assuming perfect foresight. This is e.g. done in Münster and Meibom [21;22] where the energy system model Balmorel - looking at district heating and electricity markets in Northern Europe - is used to optimise investments and operation of different Waste-to-Energy technologies. Other energy system analyses have also been applied with focus either on electricity or district heating, such as the HEATSPOT model [23;24] and the WAMMM/MARKAL model [25]. Furthermore, analyses have been made taking an offspring in the waste management system and with less focus on energy such as in the NatWaste model [26] and MIMES/ Waste model [27]. Apart from Balmorel, which maintains the chronology of time, the above mentioned energy system models use duration curves and marginal production costs of plants to determine the energy production. A similar approach is used in Dornburg et. al in 2006 [28;29], where the goal may be to find the optimal type, scale and location of waste treatment plants from an economic or energy use perspective.

Another much used optimization method when assuming perfect foresight is *mixed integer linear programming (MILP)*. Tietze-Stöckinger et al [30] for example focus on industrial waste on an inter-company level, thus, a waste management problem seen from the waste producer's side. A model is developed (LINK^{opt}) considering interactions between waste treatment, storage, transport and waste handling. In Gomes et al [31] focus is on waste management of WEEE, optimising the location of both collection and sorting centres with offset in a Portuguese case.

MinMax regret analysis is used both as a stand-alone method for waste management and as part of a hybrid model. In Chang & Davila [32], regret analysis has been used, focusing on shipping, construction, and operational costs in the waste flow. The electricity generation has been included as revenue, and is, thus, not modelled as part of the waste management problem.

One could argue that optimisation in relation to waste management does include a number of uncertainties to be included in the model. A number of papers [33-47] are focused on uncertainties and imprecise data in relation to waste management and on development of municipal waste

management models using techniques like *stochastic programming*, *fuzzy programming*, or *interval analysis*.

Table 1 Systems engineering model: Optimisation

| Method | Reference | Objectives | Focus | Optimization on |
|------------------------------------|-----------|--|---|--------------------------------|
| Linear Progr. (LP) | [21;22] | -Maximize economic utility of energy consumers (Balmorel) | WtE | Economy partly on environment |
| | [23;24] | -Minimize cost of meeting district heating demand (MODEST) | WtE | Economy |
| | [25] | -Minimize total system costs for waste and energy management (WAMMM/MARKAL) | WtE | Economy and partly environment |
| | [26;48] | -Minimize costs and emissions, for waste management (MIMES) and for an integrated waste and energy management (NATWASTE) | WtE | Economy partly on environment |
| | [28;29] | -Optimal type, scale and location of waste treatment plants (step-wise optimisation) | recycling/deposits | Economy and environment |
| Mixed Integer Linear Progr. (MILP) | [31] | -Finding best locations for collection and sorting centres, minimize costs, waste management on inter-company level including investments (LINK ^{opt}) | recycling/deposits | Economy |
| | [30] | -Minimize cost related to location of transit stations, incineration | | Economy |
| Regret Analysis | [32] | -Minimizing possible loss using MinMax IP, focus on construction of waste treatment plants, shipping, and electricity generation | | Economy |
| | [33] | -Minimizing possible loss using interval-based MinMax, focus on waste flows and capacity | recycling/deposits | Economy |
| Stochastic Progr. (LP or MILP) | [34] | -Minimizing expected costs using inexact semi-infinite MIP, focus on capacity expansion and waste flows | recycling/deposits | Economy |
| Fuzzy Logic (LP or MILP) | [35] | -Interval-valued robust programming, minimizing costs, focus on waste flows and landfill | recycling/deposits | Economy |
| | [3] | -Fuzzy parametric programming, minimizing costs of waste flow, landfill | | |
| Interval Progr. (LP or MILP) | [36] | -Interval-based possibilistic programming method for waste management with cost minimization and environmental-impact abatement under uncertainty | recycling/deposits | Economy and environment |
| Hybrid models | [37;38] | -Inexact MIP introducing uncertainty in the MIP, minimizing costs with focus on waste flow | | Economy |
| | [34;39] | -Inexact fuzzy-stochastic MIP, minimize costs in waste handling | | Economy |
| | [40] | -Fuzzy interval MIP, multi-objective minimise costs, noise impacts, and air pollutants, maximise degree of traffic service | | Economy and environment |
| | [41] | -Inexact dynamic optimization (IDOM), minimise costs in waste flow, focus on investments and environment | | Economy and environment |
| | [42] | -Two-stage stochastic programming, interval programming, and chance constrain programming integrated, costs and waste flows, long-term waste-management strategies | recycling/deposits, WtE included as price in some | Economy |
| | [43] | -Interval-parameter stochastic robust optimization, waste flows, revenue from WtE | | Economy |
| | [44] | -Fuzzy-stochastic-interval linear programming for supporting municipal solid waste management | | Economy |
| | [45] | -Superiority-Inferiority-Based Inexact Fuzzy Stochastic Programming Approach for Solid Waste management Under Uncertainty | | Economy |
| | [46] | -Interval-parameter fuzzy-stochastic programming for municipal solid waste management and planning | | Economy |
| | [47] | -Integrated Optimization Model for Environmental management under Uncertainty (IFTICIP) | | Environment |

Further refinements of the classification in Table 1 are common. Thus, distinction may be made relative to the time structure of the model such that static models (e.g. [49;50]) refer to models that treat a single time period (typically a year) while dynamic models (e.g. Balmorel [21]) handle a sequence of time periods and their relations, e.g. in relation to investment options.

While LP is the backbone of optimization, models representing nonlinearities are found, as represented by the MILP models (e.g. [31]) or regret models (e.g. [32]). However, no papers with other types of nonlinearities such as e.g. use of quadratic functions were found.

It is observed that MCDM (e.g. [13]) in fact applies optimization, but the focus is on combining or analyzing a situation with two or more criteria; this is typically done by making a parametric programming analysis with one objective and variation of one or more right hand sides (constraining values).

A majority of the models developed focus on modelling the recycling/deposit part of the waste management (e.g. [31]). Only a few models WtE technologies (e.g. [21]) and none of them integrates the two sides of the waste management, except from Olofsson (2001) [51] that soft-links waste management and district heating.

Furthermore, except from MCDM where at least two criteria are represented, the optimization models primarily focus on economic optimization (e.g. Cui et al (2011)) [33]). In a few models, environmental costs are considered as part of the optimization (e.g. Xu et al (2010)) [43]), and in only one model, the optimization focuses only on environmental management under uncertainty (e.g. Li et. Al. (2009) [42]). On the other hand, system assessment models like the LCA often focus primarily on the environmental factors (e.g. Assefa et al (2005) [5]). Focus on social aspects, such as health and noise, has only been considered by very few of the articles identified (e.g. Salvia et. Al 2002 and Dijkgraaf & Vollebergh 2004 [25;52]) and none of these apply system optimisation models,

Conclusions and discussion

As mentioned, optimisation is most relevant when one decision-maker controls the important parts of the system in focus. However, optimality in one part of the waste management problem, e.g. the recycling/deposits may influence the optimal solutions found in the other part of the waste management problem, namely the WtE, hence, broader system models are required. Only Olofsson (2001) [51] attempts to integrate the two systems, the remaining models link the subsystems by including e.g. a price or revenue from the previous/adjacent part of the waste flow.

Furthermore, it could be of relevance to consider both minimising the costs and the negative environmental impacts. Inclusion of the social aspects could also be an interesting challenge.

We have seen many papers on optimisation in the waste management category. The relevance of using different optimisation models for decisions in waste management is dependent on the context of the problem. We have seen a number of case analyses of waste management taking off-set in real cases.

The uncertainty in the waste management problem is strongly represented, possibly because a group of researchers are interested in solving the waste management problem by integrating various optimisation methods. Most of the articles focused on uncertainty come from the same group of people (e.g. [33;35;41;43;46;47]).

The papers have tried in various ways to integrate the recycling/deposit side of the waste management with the WtE side in terms of prices and revenues. More research in the field of integrating the two sides of the waste management could be very relevant.

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